

Embodied carbon as a proxy for the environmental impact of earthquake damage repair

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ABSTRACT

In evaluating the life cycle environmental impacts of buildings, the contributions of seismic damage are rarely considered. In order to enable a more comprehensive assessment of a building's environmental impact by accounting for seismic events, this project developed an environmental impact database of building component seismic damage – the largest of its kind known to date – by combining data from Carnegie Mellon University's Economic Input-Output Life Cycle Analysis (LCA) database with cost estimates of repair previously developed for FEMA's Performance Assessment Calculation Tool (PACT), a software that models probabilistic seismic damage in buildings. Fifteen indicators of environmental impacts were calculated for the repair of approximately 800 building components for up to five levels of seismic damage, capturing 'embodied' impacts related to cradle-to-gate manufacturing of building materials, products, and equipment. Analysis of the data revealed that non-structural and architectural finishes often dominated the environmental impacts of seismic damage per dollar spent in repair. A statistical analysis was performed on the data using Principal Component Analysis, confirming that embodied carbon, a popular metric for evaluating environmental impacts in building LCAs, is a suitable proxy for other relevant environmental impact metrics when assessing the impact of repairing earthquake damage of buildings.

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1. Introduction

There is a growing interest in understanding the effects of natural hazard mitigation on the environmental impact of buildings, particularly in assessing the effects of earthquakes [7,18,26,38,42,47]. Frameworks, tools, and methodologies have been developed to incorporate environmental impact assessment with earthquake hazard assessment [1,10,14,15,19,31–33,46–48], with some focusing on specific structural systems such as base-isolation [16] or reinforced concrete structures [19,22]. Seismic damage can be costly and irreparable, resulting in significant environment impacts and possible complete loss of a building. Performance-based design (PBD), however, addresses post-earthquake building survival by establishing building performance criteria in the event of an earthquake of a certain magnitude or return period [2]. The performance criteria may include certain drift or displacement limits, or allowing for immediate occupation after the event.

Through the Applied Technology Council (ATC), the U.S. Federal Emergency Management Agency (FEMA) has supported the development of methodology [3,4], databases, and analysis tools [6] to enable the probabilistic analysis of seismic performance, evaluating the metrics of repair cost, repair time, and more recently environmental impact. The work presented in this paper expands upon the existing PACT database of seismic damage estimates by calculating environmental impacts and also refining the methodology developed previously in Volume 4 of the PACT project [6]. In order to estimate the environmental impacts of different levels of seismic repair, existing construction cost estimates of the seismic repair of different building components under differing levels of seismic damage were aligned with Economic Input-Output Life Cycle Analysis (EIO LCA) databases developed by Carnegie Mellon University's Green Design Institute [13]. These 'embodied' impacts capture the cradle-to-gate emissions of building materials and products used in seismic damage repair. The ATC research team selected embodied energy and embodied carbon as the preferred environmental performance metrics due to perceived value to end users and the need to limit the number of environmental impacts tracked due to computational limitations of the probabilistic analysis. Others have identified that carbon may be a relevant proxy for commonly reported LCA impacts [7,20]. This paper presents an analysis of the

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developed database to assess if the limited metrics of embodied energy and carbon are appropriate proxies for a wider suite of environmental indicators.

This work differs from previous work done by others in that it:

- 1) creates a comprehensive database of the potential environmental impacts of seismic damage for over 800 building components, presenting the largest known database of its type;
- 2) uses Principal Component Analysis (PCA) to determine if embodied carbon (also known as greenhouse gas emissions, global warming potential, and climate change potential for the cradle-to-gate stages of the life cycle) can serve as an appropriate 'proxy' for other environmental impact measurements (such as acidification, eutrophication, human health effects, etc.) to represent the multi-faceted environmental impacts of seismic damage in buildings; and,
- 3) identifies building components from the database that are both seismically vulnerable and environmentally impactful.

This paper describes the data and methodology used to create the database, presents the environmental impact results for repair of seismic damage, and discusses the wider implications of the findings for evaluating the overall environmental impact of buildings.

2. Data, materials, and methods

2.1. Project background

This work is part of the Applied Technology Council Project 58 (ATC-58), *Seismic Performance Assessment of Buildings*, which aims to incorporate the uncertainty of seismic events into performance-based design of buildings by formulating guidelines and tools to better inform stakeholders. The Performance Assessment Calculation Tool (PACT) is a program that models buildings and outputs probabilistic damage in terms of cost of repair, time to repair, loss of life, and other performance measures (also known as *consequence functions* in the PACT terminology).

Key terms in the PACT terminology used in this paper include: 1) *fragility*, which is defined as “the vulnerability of structural and nonstructural components to damage”, and 2) *damage state* (DS), which is defined as “a condition of damage associated with a unique set of consequences” [3]. Building components have between one and five damage states defined, and lower damage states (e.g. DS1) are associated with lower levels of seismic impact (acceleration and displacement) than higher damage states. A *fragility group* is defined as “a collection of similar components or systems (e.g. reinforced concrete elements) with the same damageability and consequences of damage”, while a *performance group* is defined as “a subcategorization of fragility groups” (e.g. a concrete shear wall).

More information about the development and methodology of PACT can be found in Volumes 1 and 2 of FEMA's *Seismic Performance Assessment of Buildings* [3,4].

2.2. Goal

The overall goal of this research work is to develop a database of environmental impacts for a wide range of typical building components at different levels of seismic damage, to use the data to understand which types of building components result in higher environmental impacts per dollar spent in repair, and to determine if greenhouse gas emissions, or 'carbon', appropriately represents other environmental impact measures reported by LCA. The results are to be incorporated into PACT, enabling environmental impact to be used as another metric by which one can assess seismic performance. Structural engineers can use this data to assess the relative

value of different structural design proposals for similar buildings in order to better inform architects, building owners, and policy makers of the associated environmental impacts of their decisions. However, because the data and methods have not been critically reviewed per ISO 14044 life cycle assessment standards [23], the results should not be used to make a 'comparative assertion', or declare that one type of system is environmentally preferable to another. The primary goal of the work described in this paper is to assess if reporting LCA environmental impact can be effectively represented by a single performance metric.

2.3. Data

2.3.1. Cost estimate data

Cost estimates had previously been developed by a professional construction cost estimator for the purpose of computing the costs of repairing seismic damage of the building components in the PACT database. These cost estimates were based on a reference location in Northern California and the reference year 2011. Higher damage states typically had higher repair costs. Contractor pricing strategies and construction cost escalation were not considered, but economies of scale and efficiencies in construction practices were included [3]. The costs used for the LCA calculations were based on the P50 values, or values with a 50% likelihood of exceedance. Generally, the cost estimates were provided for each applicable damage state for approximately 70 performance groups, with some cost estimate calculations being re-used for certain fragilities. Most fragilities had between 1 – 3 damage states, and some reached damage states 4 and 5. The grouping scheme used in this analysis is shown in Table 1. For the purposes of presenting results in this paper, similar groups that contained relatively few elements were combined; *Cold-Formed Steel Structural Elements* (B106) and *Wood Light Frame Structural Elements* (B107) were combined to form *Light Frame Structural Elements*, and *Special Structures Including Storage Racks* (F101) was included with *Interior Finishes*.

2.3.2. Environmental impact data

Early research into integrating environmental impacts into PACT evaluated two different methods of generating the environmental impact data: EIO LCA and process-based LCA [5]. EIO LCA links the energy and materials required for economic activities with the environmental emissions from contributing activities in the supply chain, establishing the environmental impact of an economic activity per dollar spent in that industrial sector. Process-based LCA links quantities of materials and energy to LCA results for specific manufacturing and construction processes, and would provide advantages over EIO LCA, most notably by providing more certainty in both quantity inputs and accuracy in aligning those impacts with precise unit process LCAs.

EIO LCA was selected to model the environmental impacts of building repair because it enabled straightforward development of impacts based on the existing construction cost estimates, and also because it matched the level of detail and precision used in estimating cost and repair time in the existing PACT database. The goal and scope of the PACT tool did not require the added level of site- or material-specific precision associated with process-based LCA. Ideally, a next-generation version of PACT would generate bills of materials for repair and that would enable the efficient use of process-based LCA. Using a process-based LCA database would enhance the accuracy of the repair cost and time estimates, compare different transportation modes or material options (for example, different concrete strengths), and produce reasonable estimations of waste quantities.

The source of the environmental impact data used in this analysis was obtained from the online EIO LCA tool developed by the Green Design Institute at Carnegie Mellon University [13]. The data

Table 1

Fragility grouping scheme with typical component items.

Fragility group	NISTIR number	Number of elements in group*	Typical performance group items in fragility group
Structural Steel Elements	B103	562	Shear tabs, column base plates, column splices, braced frames (multiple types), steel connections, etc.
Reinforced Concrete Elements	B104	414	Concrete moment frames, concrete shear walls, flat slabs to column connections, concrete link beams
Masonry Vertical Elements	B105	50	Reinforced masonry walls
Light Frame Structural Elements	B106, B107	27	Light-frame steel walls (B106), light-frame wood walls (B107)
Exterior Enclosure	B20	63	Pre-cast concrete panels, light-frame exterior steel walls, light-frame exterior wood walls, glazing systems
Roof Elements	B30	22	Tile roofs, masonry chimneys, masonry parapets
Partitions	C101	20	Metal stud gypsum walls, wood stud gypsum walls
Stairs	C20	30	Prefabricated steel stair, precast concrete stair, cast-in-place stair, hybrid type stair
Interior Finishes	C30, F101	94	Finishes (wallpaper, ceramic, high finish), floor wetting, ceilings, pendant light fixture, elevators; includes special structures including storage racks (F101)
Plumbing	D20	127	Piping (potable, sanitary, chilled water, steam)
HVAC	D30	288	Chillers, cooling towers, compressors, fans, ductwork, diffusers, VAV boxes, air handlers
Fire Protection	D40	34	Piping, sprinkler drops
Electrical	D50	218	Transformers, motor control centers, switchgears, battery racks, battery chargers, generators

* Includes elements from all damage states.

includes upstream processes – such as material extraction, processing, energy input, and so forth – required to produce one million dollars' worth of product in a particular industrial sector. The model used was the US 2002 Benchmark Purchaser Price Model. The Purchaser Price Model includes transportation and mark-up for profit, appropriately reflecting the repair costs of earthquake damage from the perspective of the consumer or the building owner. The reference year of the source data is 2002, which is consistent with TRACI 1.0 [9].

The scope of the impacts assessed is limited to the cradle-to-gate impacts of the materials used to repair seismic damage or replace the building. The environmental impacts measured for this analysis include embodied carbon, embodied energy, and the set of TRACI factors available from the EIO LCA database. Excluded impacts include: construction site energy, routine material maintenance and cleaning, building operations, and waste disposal. No environmental impact is assigned to labor, as is common in industry LCAs. See Section 2.3.3 for more detail on this omission.

Based on the repair activities described in the cost estimate, industrial sectors were selected for the analysis, shown in Table 2. Given the scope of the EIO LCA database and the specificity of the work activities found in the cost estimates, it should be noted that not all industrial sectors were an exact match to the applicable repair activity. For example, *Paint and coating manufacturing* simply applied to a repair activity that involved paint or finishes, whereas *Lime and gypsum product manufacturing* applied to a wide range of activities that could encompass gypsum products, ranging from gypsum wall board to fireproofing to ceiling tile.

2.3.3. Uncertainty and limitations

Uncertainties in the EIO LCA source data include: the age of the data, uncertainties inherent in original data, incomplete original data, aggregation of data, and aggregation of industrial sectors [13]. Given the relatively old age of the EIO LCA data, the calculated environmental impacts do not reflect technological innovations that have happened in the past 15 years. Furthermore, there is a significant difference between reference dates of the EIO LCA data (2002) and the cost estimates (2011), though inflation factors were applied to attempt to account for this difference (discussed in Section 3.3). While EIO LCA has been used to evaluate buildings [11,25,36], the majority of building industry LCAs for both products and buildings have used process-based LCA data. In addition to the uncertainties surrounding EIO LCA, uncertainties in the work presented in this paper include: 1) the variability in the selection of

Table 2

List of the 25 industrial sectors included in analysis. Refer to the NAICS code for full sector name.

Sector name (abbreviated)	NAICS code	Applicable materials and construction activities
Adhesive	325520	Glue, epoxy, grout
Aluminum	33131B	Aluminum window walls/curtain walls
Clay product	32712A	Brick, ceramic tile
Cleaning	561700	Material removal and disposal
Coating	325510	Paint, finishes
Concrete	327320	Ready-mix concrete
Concrete masonry	327330	Concrete masonry unites
Electrical	335999	Mechanical and electrical modifications for repair
Flat glass	327211	Window glass replacement
Floor - carpet	314110	Carpet flooring
Floor - vinyl	32619A	Vinyl flooring
Gaskets	339991	Window gaskets
Generator	335312	Generator
Gypsum product	3274A0	Sheetrock, fireproofing, ceiling tile, soffit, etc.
Mechanical	333415	Heating, ventilation, and air-conditioning (HVAC) equip.
Moving equipment	333920	Elevators
Piping - metal	332996	Metal pipes
Piping - plastic	326122	Plastic pipes
Plastic film	326110	Plastic sheeting to protect furniture during repair
Plywood	32121A	Concrete formwork
Sawn lumber	331200	Wood frame stud walls
Steel - fabricated	321100	Manufactured steel, i.e. rebar, joists, welding processes
Steel - hot-rolled	332310	Hot-rolled steel sections, gusset plates
Stucco	327999	Stucco
Windows	332320	Windows with metal frames and doors

industrial sectors, 2) the allocation of costs to the industrial sectors, 3) the PACT cost estimates not necessarily representing the actual components in the final building, and 4) the fact that the PACT cost estimates were based on the professional judgment of a single cost estimator. The variability of the environmental impact data modeled for PACT will follow a similar mean distribution developed for cost.

Significant known environmental impacts due to seismic damage and repair not addressed by this data include 1) the trans-

Fragility $f = C1011.001a$ (Wall Partition, Type: Gypsum with metal studs, Full Height, Fixed Below, Fixed Above)
Damage state $n = DS1$

Total cost = \$1785 to repair 1300 SF of wall

	Sector j	Cost C	Environmental impact factor F for impact category i				
			GWP	AP	EP	ODP	SP
\$1785	→ Labor:	\$1460	x [0	0	0	0	0]
	→ Energy:	\$18	x [0	0	0	0	0]
	→ Cleaning:	\$38	x [3.39E-01	1.08E-03	3.26E-05	1.05E-07	1.83E-02]
	→ Coating:	\$254	x [6.90E-01	3.24E-03	9.31E-05	1.18E-06	4.90E-02]
	→ Electrical:	\$13	x [2.57E-01	1.37E-03	3.39E-05	2.18E-07	1.86E-02]
	→ Plastic film:	\$4	x [8.76E-01	3.71E-03	9.59E-05	1.74E-06	5.15E-02]
Total:			$\Sigma = [1.94E+02$	8.93E-01	2.56E-02	3.12E-04	1.35E+01]
Per dollar:			$\Sigma / \$1785 = [1.09E-01$	5.00E-04	1.43E-05	1.75E-07	7.59E-03]

Fig. 1. Example calculation demonstrating Eq. (1).

portation and disposal of waste, and 2) the transportation of materials and workers to the site. Attempts to extract estimates of material waste quantities from the construction cost estimates were found to be either too imprecise or too difficult to obtain given the selection of EIO LCA data methodology. The impacts of labor transportation (and potential temporary housing required for them) might be significant, but it would require a more complex system to model these impacts than PACT is currently capable of.

The PACT data and methodology have not yet been validated. Preliminary studies [8] comparing repair costs and downtime resulting from PACT to those of buildings damaged in an observed earthquake have shown reasonable correlation, yet more work remains to test the current data. Furthermore, confidence in the background PACT fragility data decreases as the assessment deviates further away from the date of the construction cost estimates (2011), the date of the EIO LCA data (2002), and the geographic location of the default region (Northern California). It should be noted that EIO LCA data was developed for the U.S., and so these results would not be applicable outside of the U.S. The probabilistic evaluation within PACT attempts to capture uncertainty, yet uncertainty is modeled using rough estimates and professional judgment. Validation will be a critical step to help assess if these rough estimates are adequately precise to enable effective design decision making.

Studies comparing different LCA datasets [21,29,34,41] indicate that while LCA results using different tools or data use different assumptions and produce different results, comparisons between different options show consistent relative impacts (e.g. both increasing) when using different databases. EIO LCA studies typically estimate environmental impacts to be greater than those using process-based data [35]. Given these sources of uncertainty, the total environmental impact magnitude should be considered less meaningful than the relative difference between options when comparing between different building scenarios, which is a key application of a design tool like PACT.

3. Calculations

3.1. Calculation of environmental impact

The estimate of environmental impacts is directly derived from the construction cost estimate. For each fragility and damage state, the cost of each repair activity (for example, “Re-weld, repair shear tab, replace shear bolts”) was first disaggregated and allocated to

four main categories – *Labor*, *Energy* [consumption], *Rental Equipment*, and *Materials* – using professional judgment from the construction cost estimator who created the original PACT repair estimates. Then, the material costs were further allocated to one or more industrial sectors selected from the EIO LCA database based on the materials or services required in that repair activity. After the repair costs were allocated into the sectors, the sector costs were then multiplied by the environmental impact factors per dollar from the EIO LCA database to obtain the set of environmental impacts per dollar for that fragility and damage state. Finally, the calculated environmental impact was divided by the total repair cost of the fragility to reflect the impact per dollar spent (or by the total quantity to reflect the impact per unit measurement).

To summarize the calculations, the environmental impact E (in environmental impact units per dollar cost of repair) can be formulated as shown in Eq. (1):

$$E_i^{f,n} = \frac{\sum_j C_j^{f,n} F_{i,j}}{\sum_j C_j^{f,n}} \quad (1)$$

where i = impact category; f = fragility; n = damage state; j = industrial sector; $C_j^{f,n}$ = repair cost of fragility f in damage state n incurred in sector j ; $F_{i,j}$ = EIO factor of impact category i for sector j (in environmental impact units per dollar). For example, the embodied carbon of partition walls in damage state 1 is equal to the sum of the costs in the relevant sectors times their respective EIO sector factors, and divided by the overall cost to normalize to embodied carbon per dollar spent in repair. The EIO LCA database reports a wide range of environmental impact categories, ‘ i ’ in Eq. (1), per the U.S. EPA’s TRACI impact assessment categories. The seven impact categories selected to evaluate environmental performance include: global warming potential (embodied carbon), acidification, eutrophication, ozone depletion, smog and energy use (embodied energy). These are the metrics commonly used to evaluate LCAs by building industry tools and rating systems in North America [12,45]. See Fig. 1 for an example calculation.

3.1.1. Sector cost allocations

To summarize the disaggregation of the cost estimate data into the industrial sectors and the non-impact categories (*Labor*, *Energy*, and *Rental Tools*), Fig. 2 presents the average percentage sector allocations by fragility group (all applicable damage states were included in the average). This figure is only meant to illustrate at a

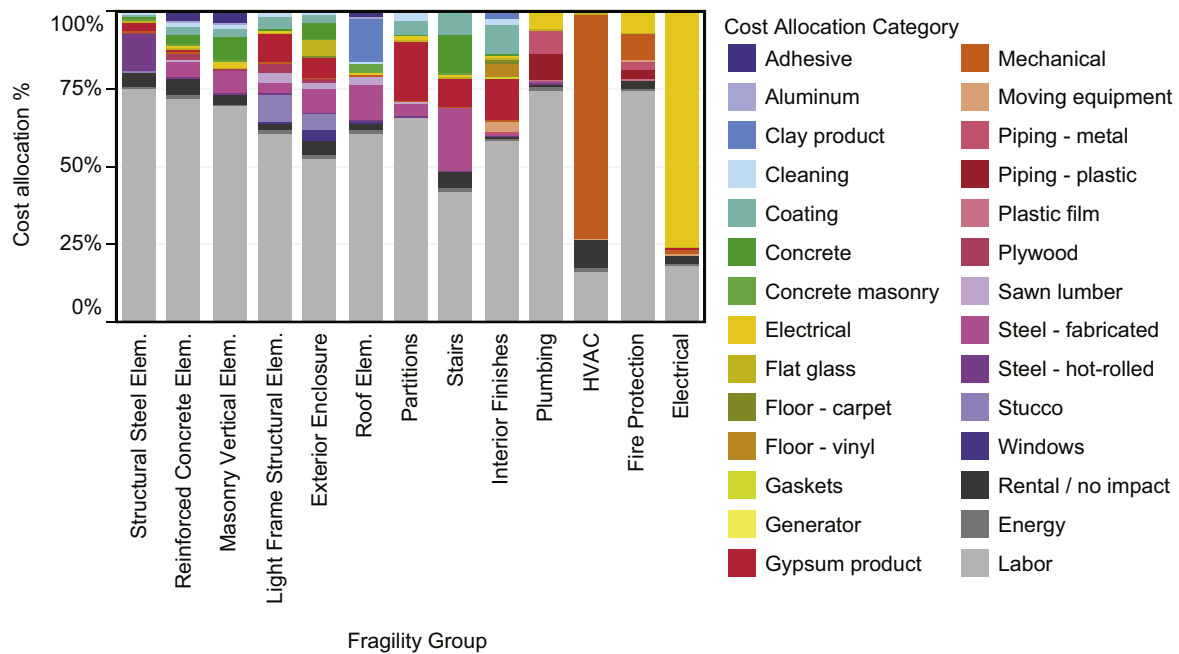


Fig. 2. Percentage distribution of cost allocations for fragility groups, including non-impact sectors (Rental, Energy, and Labor shown in shades of gray), averaged across damage states within each fragility group.

glance how the sector costs allocations were distributed, since the number of colors required for the 25 sectors makes it difficult to distinguish between individual sectors.

From Fig. 2 it can be seen that *Labor* (color: light gray) forms the majority of the sector costs (40–70%) in most cases, except for HVAC (orange) and *Electrical* (golden yellow), which had higher costs than *Labor* because these categories typically require the replacement of complex, expensive equipment, resulting in lower on-site labor costs than that of the simple materials that must be compiled by hand on site. Given the relatively large contribution of construction labor to overall construction costs, additional research into the environmental impacts of disaster construction labor would be valuable. Some prominent sectors that occur across multiple fragility groups include: *Steel - hot-rolled* (violet), *Steel - fabricated* (orchid), *Coating* (cyan), *Concrete* (dark green), *Gypsum product* (red), and *Electrical* (golden yellow).

3.2. BEES score

Given that a primary goal of this analysis is to understand if embodied carbon is an appropriate proxy for the other environmental impacts, an ‘environmental score’ that encapsulates multiple environmental metrics was computed as a possible metric of comparison with embodied carbon. The Building for Environmental and Economic Sustainability (BEES) Environmental Performance Score [27] was selected as the weighting metric because it had been developed specifically for building products by the National Institute of Standards and Technology (NIST) in the United States. The BEES Score considers the relative importance of each impact category by weighted factors and the relative quantity of the impact category by normalization. An impact such as ozone depletion, which is currently managed by international cooperation and has low and diminishing emissions [49], has a lower impact on the final score than carbon, which is perceived to have high importance and generates high emissions in the building sector.

The BEES Environmental Performance Score (EPS) was calculated in accordance with the Appendix A of the BEES Technical Manual and User Guide [27] and can be formulated as shown in

Eq. (2).

$$EPS^{f,n} = \sum_i \frac{E_i^{f,n} W_i}{N_i} \quad (2)$$

where $E_i^{f,n}$ = environmental impact of impact category i for fragility f and damage state n in environmental impact units per dollar cost of repair (see Section 3.1); W_i = BEES stakeholder panel weight for environmental impact category i ; N_i = normalization value for environmental impact category i .

3.3. Adjusting for inflation and geographic location

To adjust for the difference in reference years between the EIO LCA data (2002) and the PACT cost estimation data (2011), an inflation factor was applied. The inflation factor was estimated to be 1.45 based on several indices: Engineering News Record Building Construction Index [17], Marshall & Swift [30], and the Producer Price Index [44]. The inflation factor for this time period was selected to match the producer price index of 1.45 which resulted in being approximately the average of high and low estimates over that time period. Of note, the lower the inflation rate assumed, the higher the resulting environmental impact estimate. The relative difference between different repair estimates will not be significantly impacted by the choice of inflation rate. The environmental impacts per \$₂₀₀₂ were divided by 1.45 to convert 2002 to values to 2011 values.

The PACT electronic tool accounts for inflation with respect to the reference year of 2011. As for geographic location, the PACT electronic tool accounts for differences in construction costs due to location with respect to the reference location of Northern California.

3.4. Statistical methods

The linear relationship between two variables can be measured by their correlation, but a correlation does not capture the joint relationship between three or more variables. One popular technique

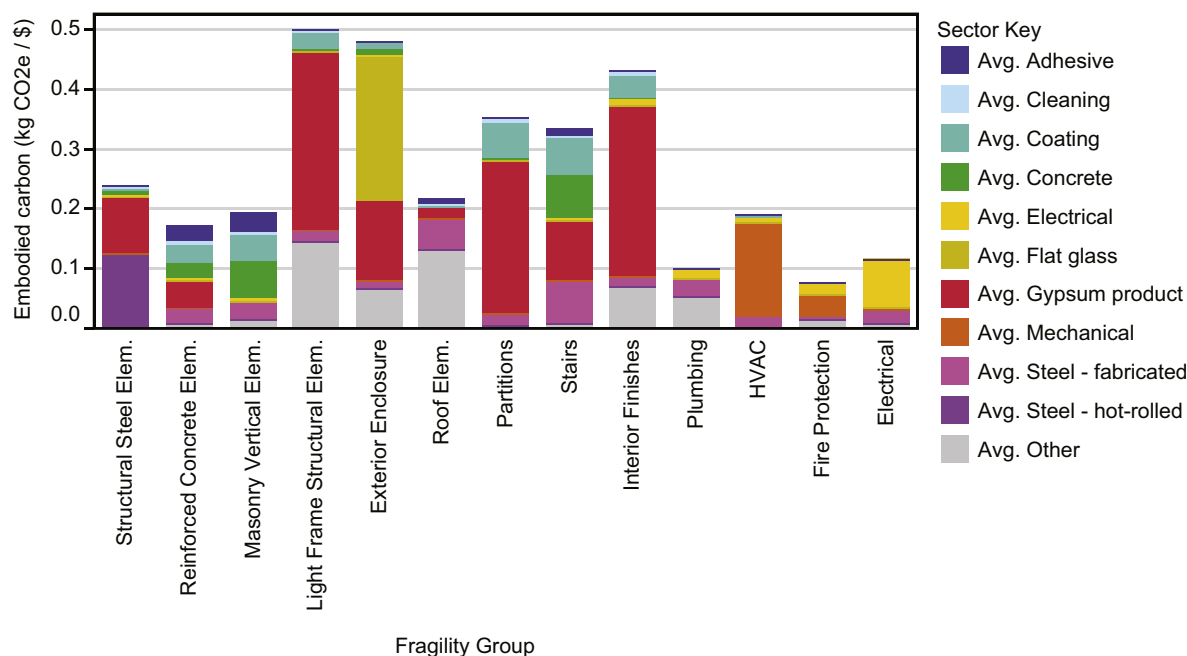


Fig. 3. Average sector contributions to embodied carbon by fragility group.

to measure the linear relationship between three or more variables is Principal Component Analysis (PCA).

PCA is a mathematical technique that decomposes the variance of a set of variables [24]. Specifically, PCA transforms the original set of variables into 'principal components,' which are a new set of variables that are orthogonal linear combinations of the original variables. The principal components are determined such that the first component maximizes the variance of the data. Each subsequent component maximizes the residual variance after the previous components are removed. The two main outputs of PCA are the principal component representation of each data point and a 'loading table' that maps the original variables to the principal components.

When a majority variance (>90%) is explained by the first few principal components, the data is considered to have a low 'effective dimension': the majority of variability in the data is along the first few principal components. In this case, the first few principal components can serve as a proxy for the full data and is the reason why PCA is used for dimension reduction [28,40].

4. Results and discussion

The primary result of this project is a database of environmental impacts for common building components undergoing seismic damage. The EIO database enabled the generation of fourteen environmental impact metrics for nearly 2000 different damage estimates based on 802 different building components, categorized into approximately 70 performance groups. The PACT tool and FEMA methodology report will include only two of the resulting metrics – embodied energy and embodied carbon – but for further analysis in this paper, five environmental metrics typically tracked in building industry initiatives (such as the United States Green Building Council LEED program [45] and NIST's BEES software) as well as the BEES Environmental Performance Score were selected to evaluate the use of embodied carbon as a proxy for other environmental impacts. This section also explores the embodied carbon generated per dollar spent repairing various building components.

Table 3

Loading factors for environmental impact categories on first three principal components. Values correlated to the principal components PC1 and PC2 are bolded.

Impact category	PC1	PC2	PC3
Embodied carbon	0.98	0.15	−0.06
Acidification (air)	0.99	0.07	0.11
Eutrophication (air)	0.98	0.12	0.13
Eutrophication (water)	0.92	−0.14	−0.35
Ozone depletion	0.54	−0.84	0.09
Smog (air)	0.98	0.11	0.13
Embodied energy	1	0.02	−0.02
BEES Environmental Impact Score	0.99	0.13	−0.01

4.1. Embodied carbon as a proxy for other environmental impacts

To determine if embodied carbon could be used as a valid proxy for other environmental impacts, Principal Component Analysis was performed on the database. The resulting loading factors for the first three principal components are shown in Table 3. It was observed that the loading factors were quite high (above 0.90) for principal component 1 (PC1) for all of the impact categories except for ozone depletion, indicating that embodied carbon is closely correlated with the other environmental impact categories – except for ozone depletion – and can thus serve as an appropriate proxy for these other environmental impacts.

Considering the recent observations that the ozone hole is healing [39] as a result of the Montreal Protocol [43] and that CFC's play a negligible role in the building industry material production, ozone depletion can be considered of low relevance when evaluating building product embodied impacts.

4.2. Embodied carbon by selected performance groups and damage states

Given that embodied carbon can be used as a representative metric of overall environmental impacts, this section explores the embodied carbon results of the database in more detail.

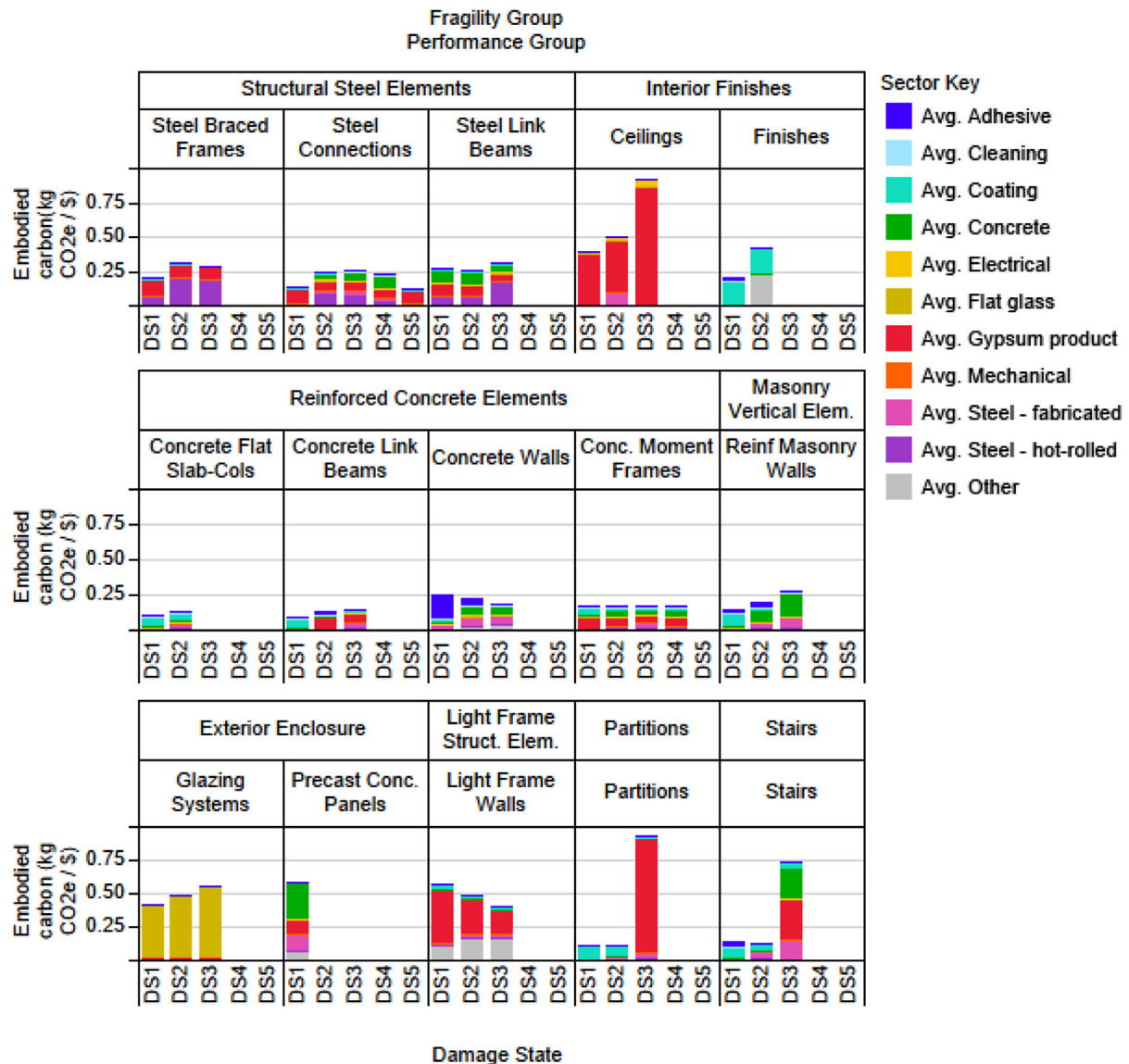


Fig. 4. Average embodied carbon of 15 selected performance groups, broken down by industrial sector (color) and damage state.

Fig. 3 presents the sector averages of embodied carbon per dollar for the fragility groups, averaged across the fragilities and applicable damage states. Only the top contributing ten sectors are shown for clarity, and the remaining are grouped into a gray *Other* category. It should be noted that for an individual fragility, the distributions of sectors may differ from the group average shown.

From Fig. 3, it can be observed that *Light Frame Structural Elements*, *Exterior Enclosures*, and *Interior Finishes* have the highest overall average impact per dollar spent in repair. These three fragility groups feature prominent use of high-impact sectors, such as *Gypsum product*, *Flat glass*, and *Concrete*. Both gypsum and glass require a large amount of energy in manufacturing [13] and this effect is exacerbated by their physical fragility and the quantities typically found in modern buildings.

To examine the building components in more detail, the fifteen performance groups with the greatest number of items (after being grouped into similar categories, i.e. all steel frames in one category, all concrete walls in another category, and not including the *Plumbing*, *HVAC*, *Electrical* groups because they have the lowest impacts on average) are shown in more detail in Fig. 4, which also includes the distinction between damage states. As with Fig. 3, only

the top 10 contributing industrial sectors are shown; the remaining sectors are grouped into *Other*.

From Fig. 4, it can be seen that although higher damage states may be expected to have higher environmental impacts, this was not always the case, since some of the repair activities that occurred at higher damage states were more costly due to labor or energy-intensive activities and had low material contributions, thus reducing the environmental impact per dollar. The final result ultimately depended on the materials and cost calculations of the fragility environmental impact calculations.

5. Conclusion

EIO LCA data (Purchaser Price Model, US 2002) from Carnegie Mellon University Green Design Institute was applied to a set of cost estimate calculations previously formulated for the PACT tool to analyze the environmental impacts of seismic damage in building components.

From analyzing the database of calculated environmental impacts, it was observed that gypsum product had the highest environmental impact as measured by embodied carbon and embodied

energy per dollar, and glass products were high as well. Given that current building codes focus on protecting life safety rather than building value and that even most advanced performance based structural designs focus on enhancing structural performance, it is not surprising that the range of damage to the non-structural components is more extreme, often requiring full replacement of components rather than partial repair of structural components. Considering how prevalent these environmentally intensive materials are in modern construction, it might be worth increasing the protection of these vulnerable building components by investing more in the structural components of a building, which produce less of an environmental impact per dollar.

This database, with nearly 2000 items across six environmental impact metrics, also provided the opportunity to determine if embodied carbon – a commonly used indicator of environmental impact – could be a representative proxy for the other impact categories through statistical analysis. The final embodied energy and carbon results are published [37] and will be integrated into the next version of the PACT software. Through Principle Component Analysis, it was determined that embodied carbon is an acceptable proxy for other environmental metrics, affirming the practice of using carbon and embodied energy as primary measures of environmental impact.

The following are possible next steps for future research in this area of study:

- Test the data within the context of whole building analysis of representative case study buildings.
- Update the EIO LCA database to reference more current economic and environmental data, and include estimates of data variability to address the range of manufacturing processes and activities within industrial sectors.
- Evaluate the environmental impact of construction labor transportation in both conventional construction and disaster response scenarios.
- Create process-based LCA studies for dominant fragility groups in order to gain confidence in the order of magnitude of the EIO LCA data.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.enbuild.2017.12.065](https://doi.org/10.1016/j.enbuild.2017.12.065).

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